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Optical Performance of Low Concentration Ratio Reflective and Refractive Concentrators for Photovoltaic Applications

A. Algarue[a], S. Mahmoud[a], R.K. AL-Dadah[a]*

[a]*School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham,United Kingdom. B15-2TT*

Abstract

Solar concentrators have the potential to replace the expensive PV cells with cheaper optical elements without affecting the overall output of the solar panel. Small scale concentrators with low concentration ratios offer the advantage of light weight, small size and easy to install without the need of tracking. Such concentrators use either reflective or refractive optical devices to focus the solar light onto a photovoltaic surface and increase its power output. Using advanced ray tracing techniques, this work investigates the optical performance of low concentration ratio reflective and refractive concentrators. Three different geometries of reflective concentrators and two geometries of refractive concentrators were investigated under the same range of concentration ratios. Results showed that both types of concentrators have similar optical efficiency for concentration ratios up to 10. For concentration ratios above 10, the performance of reflective concentrators has deteriorated significantly while the refractive concentrators have retained their high optical efficiency highlighting the potential of refractive concentrators.

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*Keyword:*Optical performance; low concentration; reflective; refractive; Fresnel lenses; ray tracing

1. Introduction

Solar concentrators have the potential to increase the utilisation of PV cells in domestic applications due to increased solar radiation input which leads to enhanced electrical output per cell. Such concentrators with low concentration ratios [1] are compact, light-weight and they do not need tracking devices with their materials cost being less than that of the PV cells. For concentrating the solar radiation onto the PV cells, generally there are two types of concentrators namely, reflective [2], and refractive [3]. Ray tracing technique is a powerful tool that uses laws of reflection and refraction to analyse the optical performance of solar concentrators by predicting the amount of lost (reflected away from the receiver) solar rays compared to those reflected / refracted ones [4].

* Corresponding author. Tel.: +44(0) 121 4143513; fax: +44 (0) 1214143958.
E-mail address: r.k.al-dadah@bham.ac.uk.

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2. Methodology

In this work, OptisWorks ray tracing software has been used to investigate the optical performance of three different reflective concentrator geometries and two refractive (Fresnel lens) concentrators. Fig 1 shows the geometries of the reflective concentrators, they are: Squared Miniature Concentrator (SMC), Hexagonal Miniature Concentrator (HMC) and Circular Miniature Concentrator (CMC). Fig 2(a) shows the general layout of the Fresnel lens (refractive concentrator) and Fig 2(b) details the geometry of two different Fresnel lens configurations (point focus (PFL) and modified design for spreading rays on the receiver (MFL)). Where R1,R2, R3, R4….Rn represent the distance of extreme paraxial ray from the optical axis for every groove, α and ά are the facet angle for the point focus and modified design of Fresnel lens respectively. Also, h and ḣ are the groove height for the point focus and modified designs of Fresnel lens respectively and f is the focal length. All the five concentrators were investigated for concentration ratios of 6, 8, 10, 15 and 20. Table 1 shows the dimensions for the five concentrator geometries where W: square aperture width, S: hexagonal aperture side, D: circular aperture diameter, H: concentrator height and *f*: Fresnel lenses focal length.

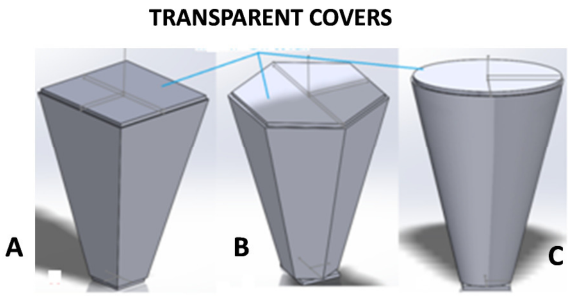

Fig. 1. Three reflective concentrators: A- (SMC), B (HMC) and C (CMC),

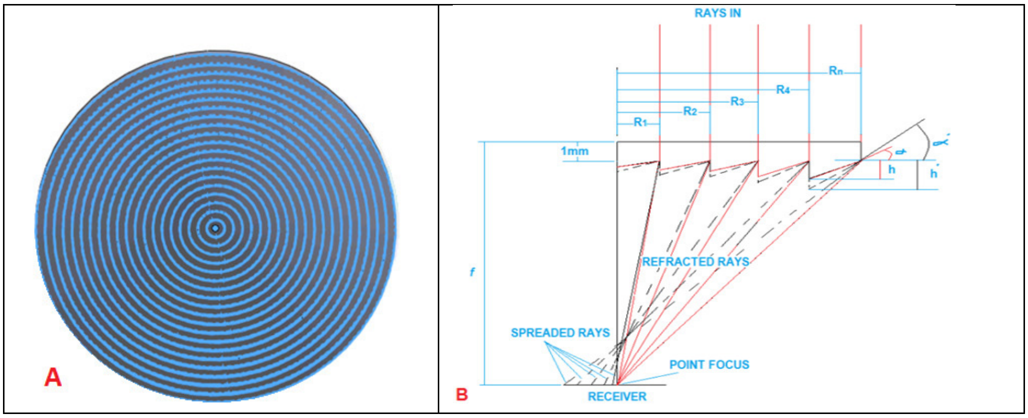

Fig. 2. A- Fresnel lens; B- Schematic diagram for the design of Fresnel lens.

Table 1. Concentrators Dimensions

CR	SMC Inlet Aperture	HMC Inlet Aperture	CMC Inlet Aperture	PFL Inlet Aperture	MFL Inlet Aperture
6	W= 24.49mm	S= 15.2mm	D= 27.64mm	D= 27.64mm	D= 27.64mm
8	W= 28.28mm	S= 17.55mm	D= 31.92mm	D= 31.92mm	D= 31.92mm
10	W= 31.62mm	S= 19.62mm	D= 35.68mm	D= 35.68mm	D= 35.68mm
15	W= 38.73mm	S= 24.03mm	D= 43.7mm	D= 43.7mm	D= 43.7mm
20	W= 44.72mm	S= 27.75mm	D= 50.46mm	D= 50.46mm	D= 50.46mm
Receiver Dimensions	W= 10mm	S= 6.2mm	D= 11.28mm	D= 11.28mm	D= 11.28mm
Height/Focal length	H=50mm	H=50mm	H=50mm	*f* =50mm	*f* =50mm

The material used for the transparent cover of the reflective concentrators shown in Fig 1 is PMMA with a thickness of 1mm and transmissivity of 88% while the material used for the internal surfaces has a reflectivity of 95%. Also the PMMA material was used for the PFL and MFL Fresnel lenses due to its advantages of having long lifetime under the sunlight with high resistant to oxidative photo-degradation, no damage by UV [5], transparent to most of solar spectrum wavelengths, low cost and suitable for mass production processes such as moulding [6].

3. Results and discussion

Using OptisWorks software, Fig 3 shows the solar flux distribution at the receivers of the various concentrators used at concentration ratio of 10. It can be seen that for the SMC and HMC concentrators, the flux is distributed over the receiver area uniformly, with lower flux density in the centre of receiver (Fig 3(A) and Fig 3(B). On the other hand, the flux distribution of the CMC shown in Fig 3(C) is covering all the receiver area, but with very high concentration (up to 20,000Wm^{-2}) at the centre of the receiver. For the Fresnel lenses, the point focus PFL produced high concentration at very small region at the centre of the receiver (Fig 3(D)) which is not desirable since most of the receiver is subjected to a much lower solar flux. Therefore, the facet angle α was modified to α' and the groove height h was changed accordingly to h', so that the refracted rays will spread over a wider receiver area as shown in Fig 2(b) in dotted lines. Fig 3(E) shows that the flux distribution of the MFL is uniform covering most of receiver area and taking ring shape.

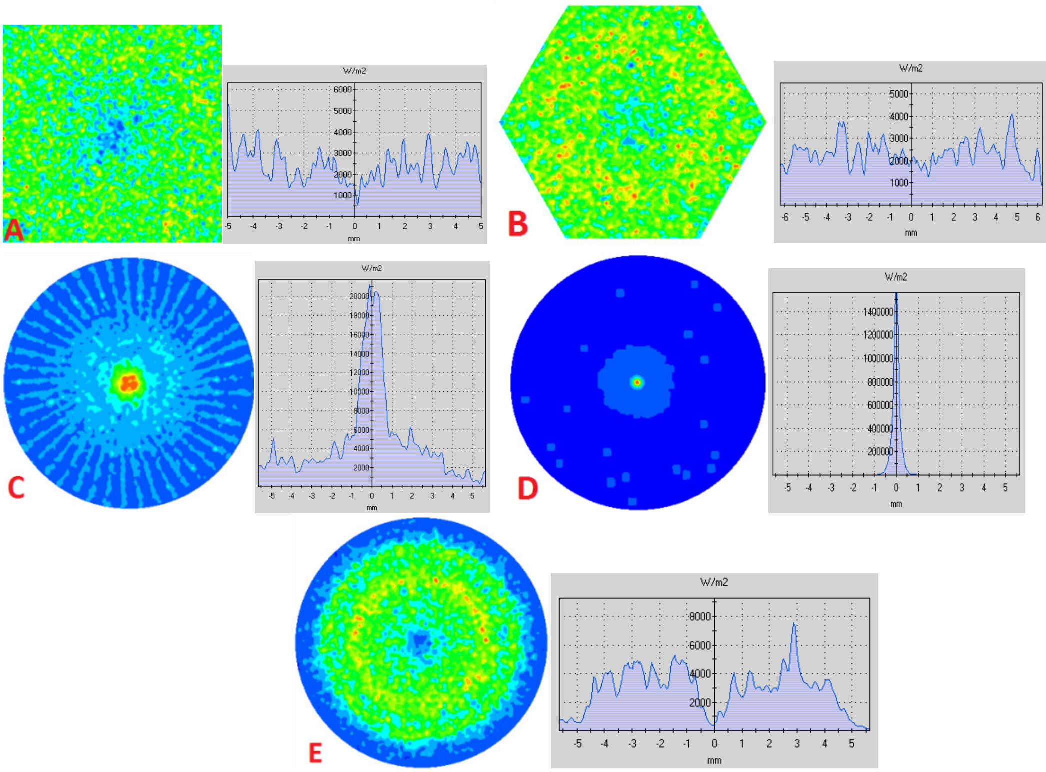

Fig. 3. Flux distribution on the receiver surface at CR=10 for: A- SMC, B- HMC, C- CMC, D- PFL and E- MFL.

Fig 4 shows the variation of the optical efficiency with concentration ratio for all the concentrators investigated. Results showed that both types of concentrators have similar optical efficiency (80 to 82%) for concentration ratios up to 10. But for concentration ratios above 10, the performance of reflective concentrators has deteriorated significantly down to 30% at concentration ratio of 20. The refractive concentrators have retained their high optical efficiency close to 80%, highlighting the advantages of refractive concentrators over reflective ones. Fig 5 shows the flux distribution at the receivers of the PFL and MFL concentrators at concentration ratio of 20. It is clear from this figure that the MFL still produce more uniform distribution of the solar flux compared to the PFL.

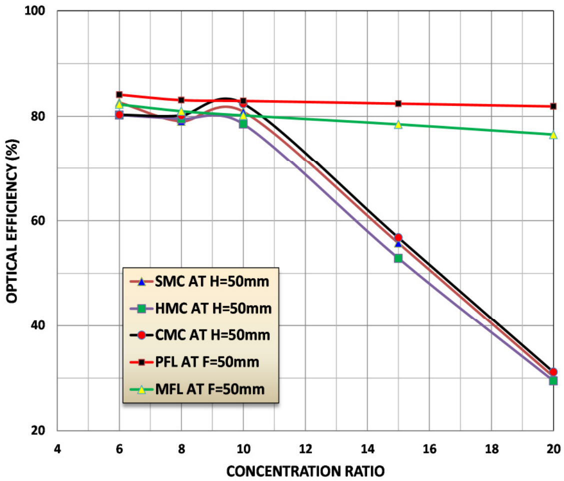

Fig. 4. Optical efficiency of the five concentrators at concentrating ratios ranging from 6 to 20.

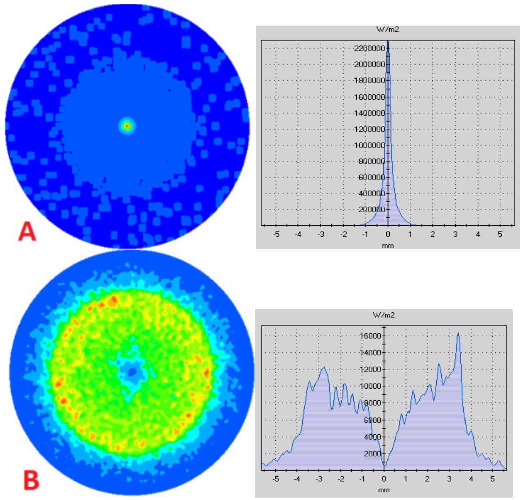

Fig. 5. Flux distribution on the receiver surface at CR=20 for: A - PFL and B- MFL.

4. Conclusions

Ray tracing technique is a powerful tool for analysing the optical performance of solar concentrators and optimising their designs. Results of ray tracing simulation showed that reflective and refractive concentrators have similar optical efficiency (80%) for concentration ratios up to 10. But for concentration ratios above 10, the performance of reflective concentrators deteriorated significantly down to 30% at concentration ratio of 20 while the refractive concentrators retained their high optical efficiency close to 80% at concentration ratio of 20, highlighting the potential of refractive concentrators.

Generally refractive concentrators tend to focus the radiation at small area of the receiver, therefore, facet angle and groove height can be modified to produce more uniform receiver flux distribution.

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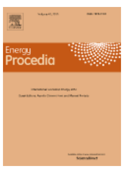

Biography

Abdulmaged Algareu is a PhD research student at the School of Mechanical Engineering of the University of Birmingham. He graduated with MSc in Production Engineering from Tripoli University-Libya. Currently he is working on optimizing a small scale concentrated PV system for domestic application.